

Frame Coalescing in Dual-Mode EEE

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Abstract—The IEEE has recently released the 802.3bj standard that defines two different low power operating modes for high speed Energy Efficient Ethernet physical interfaces (PHYs) working at 40 and 100Gb/s. In this paper, we propose the use of the well-known frame coalescing algorithm to manage them and provide an analytical model to evaluate the influence of coalescing parameters and PHY characteristics on their power consumption.

Index Terms—Energy efficiency, IEEE 802.3bj, Energy Efficient Ethernet.

I. INTRODUCTION

To reduce energy consumption of Ethernet links, the IEEE published in 2010 the IEEE 802.3az standard [1], known as *Energy Efficient Ethernet* (EEE). This norm provides a new operating mode to be used in Ethernet physical interfaces (PHYs) when there is no data to transmit. When PHYs are in this low power idle (LPI) mode, they only draw a small fraction of the power needed for normal operation, although they are unable to send traffic through their attached links. Probably, the most natural way to manage EEE interfaces consists of entering LPI whenever the transmission buffer becomes empty and restoring normal operation when there is new traffic to transmit. However, this approach is not very efficient since PHYs consume about the same power during state transitions (to/from the LPI mode) as in the active state and transition times are of the same order than a single frame transmission time. In fact, energy savings can be greatly improved if the number of state transitions is significantly reduced, for example, just making that PHYs wait to first accommodate a few frames in the transmission buffer before exiting LPI (*frame coalescing*). EEE has shown to be very effective to reduce energy consumption of 100Mb/s, 1Gb/s and 10Gb/s Ethernet links, specially when some coalescing control policy is applied [2], [3].

The problem of relatively long transition times is even more severe in 40Gb/s and 100Gb/s Ethernet PHYs since, under these higher rates, transmission times are significantly lower while transition times remain similar. This issue has been recently addressed in the IEEE 802.3bj amendment [4] that defines two different low power modes for high speed interfaces: *Fast-Wake* and *Deep-Sleep*. In the Fast-Wake state, only some PHY components can be turned off since clock synchronization must be maintained for keeping attached links aligned. As a result, this mode requires very short transition times to resume normal operation but it still draws a significant portion of the power consumed when active (70-80%) [5]. On the contrary, PHYs in the Deep-Sleep state consume a very little amount of energy since all signaling is stopped (10-20%) but this mode requires considerably longer transition times.

[6] shows that combining these two low power modes in high speed EEE links allows energy savings that may be not achievable with just a single LPI mode. However, this simulation study assumes that PHYs in any of the two low power modes turn back to active as soon as new traffic is ready for transmission. In this paper, we develop an analytical model to evaluate the energy savings that can be obtained when dual-mode PHYs apply frame coalescing and wait to queue some frames in the transmission buffer before returning to active.

The rest of the paper is organized as follows. Section II presents the basic operations of dual-mode EEE interfaces using frame coalescing. In Section III we develop an analytical model to compute their power consumption. We next particularize this model to Poisson traffic in Section IV. In Section V, we validate our analysis through simulation. Finally, the conclusions are summarized in Section VI.

II. DUAL-MODE EEE OPERATIONS

Figure 1 depicts an example of the main operations of dual-mode EEE interfaces. Clearly, for maximizing energy savings, a dual-mode EEE interface should be put to sleep every time its transmission buffer gets empty. Then, after a short transition of length T_{AtOF} , the interface enters the Fast-Wake mode. [6] assumes that the interface will remain in Fast-Wake until a frame arrives or for a maximum period of length T_{idle} . In the former case, the interface would directly return to the active state after a transition of length T_{FtoA} while, in the latter one, it would transition to Deep-Sleep after a T_{FtoD} period. As suggested in the Introduction, frame coalescing can be applied to these interfaces to improve their energy savings. Consequently, we propose that PHYs switch to Deep-Sleep as long as less than Q_f frames arrive during the T_{idle} period. Otherwise, they would resume normal operation when the Q_f -th frame arrives.

On the other hand, [6] also assumes that the interface abandons the Deep-Sleep mode as soon as a new frame arrives. Again, we can apply frame coalescing to this mode so that the interface remain in Deep-Sleep until Q_d frames are buffered for transmission. We assume that $Q_f \leq Q_d$ to avoid useless transitions to Deep-Sleep. Eventually, a long transition of length T_{DtoA} will be required to return to the active state.

Clearly, coalescing frames into bursts increases their delay. So, to avoid excessive delays, the maximum time an interface can be in a low power mode (since the first frame is buffered for transmission) should be limited.

III. ENERGY CONSUMPTION MODEL

In this section we will develop an analytical model to evaluate the influence of coalescing parameters and PHY characteristics on energy consumption. We assume that frame

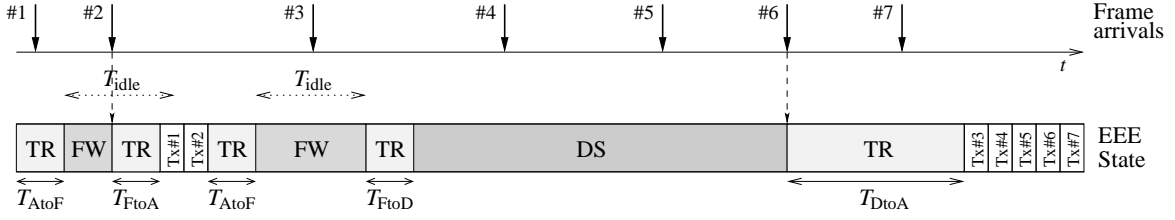


Fig. 1. Dual-mode EEE operations. Example with $Q_f = 2$ frames and $Q_d = 4$ frames.

arrivals follow a general distribution with independent and identically distributed interarrival times I_n , $n = 1, 2, \dots$, and average arrival rate λ . We also assume that service times follow an arbitrary distribution function with mean service rate μ . Obviously, the utilization factor $\rho = \lambda/\mu$ must be less than 1 to assure system stability. Finally, we assume that the interface has a transmission buffer of infinite capacity.¹

Fig. 2 shows how the transmission buffer of a dual-mode EEE interface evolves. Time intervals when frames are not being transmitted are *inactive periods* and may be composed of several *transition periods* (T_{AtoF} , T_{FtoA} , T_{FtoD} , T_{DtoA}) and two *sleeping periods* (T_f , T_d) in which the interface is in one of the two defined low power modes. Within the inactive period there is also an *empty period* T_e that comprises the time elapsed between the interface is put to sleep and the arrival of the subsequent first frame. During this empty period no frames are buffered in the transmission queue of the interface. The time interval when the interface is transmitting frames is the *busy period* T_{on} . Finally, an inactive period followed by a busy period forms a *coalescing cycle* T_{cycle} .

A. Energy Consumption

Let $E[P]$ be the mean power consumption for a given interface that never enters a low power mode and $E[P_{EEE}]$ the mean power consumption for a dual-mode EEE interface. Clearly, $E[P_{EEE}]$ depends on the proportion of time the interface spends in each possible state:

$$\begin{aligned} E[P_{EEE}] &= \rho_f E[P_f] + \rho_d E[P_d] + \rho_{tr} E[P] + \rho_{on} E[P] \\ &= \rho_f E[P_f] + \rho_d E[P_d] + (1 - \rho_f - \rho_d) E[P], \end{aligned} \quad (1)$$

where $E[P_f]$ and $E[P_d]$ are the mean power consumed in the Fast-Wake and the Deep-Sleep modes, and ρ_f , ρ_d , ρ_{tr} and ρ_{on} are, respectively, the fractions of time in which the interface is in Fast-Wake, Deep-Sleep, transitioning between states and awake. Note that it is assumed that the interface consumes about the same power during transitions as in the active state since many components of the transceivers have to be operative during the state changes. Immediately, the energy consumed on a dual-mode EEE interface compared with that consumed on an interface that it is always active is given by

$$\phi = \frac{E[P_{EEE}]}{E[P]} = 1 - (1 - \phi_f)\rho_f - (1 - \phi_d)\rho_d, \quad (2)$$

¹Note that, if the queue thresholds are chosen carefully, additional frame losses should be negligible. For example, an interface transitioning to awake from Deep-Sleep will only receive, in average, λT_{DtoA} more frames before it is active again. Therefore, the buffer should be correctly dimensioned to accommodate, at least, $Q_d + \mu T_{DtoA}$ frames plus a safety margin.

where $\phi_f = E[P_f]/E[P]$ and $\phi_d = E[P_d]/E[P]$ are the portions of the active mode energy consumption demanded when the interface is in Fast-Wake and Deep-Sleep, respectively, and shape the efficiency profile of the interface.

The factor ρ_f can be calculated as the ratio between the mean duration of a Fast-Sleep period and the mean duration of a coalescing cycle:

$$\rho_f = \frac{E[T_f]}{E[T_{cycle}]} = \frac{E[T_f]}{E[T_f] + E[T_d] + E[T_{tr}] + E[T_{on}]} \quad (3)$$

In addition, we know that the utilization factor ρ satisfies $\rho = E[T_{on}]/E[T_{cycle}] = E[T_{on}]/(E[T_f] + E[T_d] + E[T_{tr}] + E[T_{on}])$ since, as long as the interface is awake, it is transmitting queued frames. Rearranging terms, $E[T_{on}] = \rho(E[T_f] + E[T_d] + E[T_{tr}]/(1 - \rho))$ and, substituting this into (3), we get

$$\rho_f = (1 - \rho) \frac{E[T_f]}{E[T_f] + E[T_d] + E[T_{tr}]} \quad (4)$$

Following the same approach, ρ_d can be calculated as

$$\rho_d = (1 - \rho) \frac{E[T_d]}{E[T_f] + E[T_d] + E[T_{tr}]} \quad (5)$$

Finally, substituting (4) and (5) into (2), we obtain that

$$\phi = 1 - (1 - \rho) \frac{(1 - \phi_f)E[T_f] + (1 - \phi_d)E[T_d]}{E[T_f] + E[T_d] + E[T_{tr}]} \quad (6)$$

In short, to compute the energy consumption of a dual-mode EEE interface, the average lengths of the Fast-Wake, Deep-Sleep and transitioning periods must be obtained.

B. Average Duration of Transitioning Periods

Every coalescing cycle starts with a transition from active to the Fast-Wake mode of length T_{AtoF} . Then, if the interface never enters the Deep-Sleep mode during the cycle, it will eventually resume normal operation directly from Fast-Wake after a transition of length T_{FtoA} . Conversely, if the Deep-Sleep mode is reached after a transition from Fast-Wake (T_{FtoD}), the interface will finally return to active after a longer transition of length T_{DtoA} . Therefore, the average duration of the transitioning periods can be obtained as

$$E[T_{tr}] = T_{AtoF} + (T_{FtoD} + T_{DtoA})p_d + T_{FtoA}(1 - p_d), \quad (7)$$

where p_d is the probability that the interface enters the Deep-Sleep mode. Recall that the interface transitions to Deep-Sleep just after a T_{idle} period in the Fast-Wake mode if less than Q_f frames are queued for transmission, so

$$p_d = \sum_{i=0}^{Q_f-1} \Pr[A(T_{AtoF} + T_{idle}) = i], \quad (8)$$

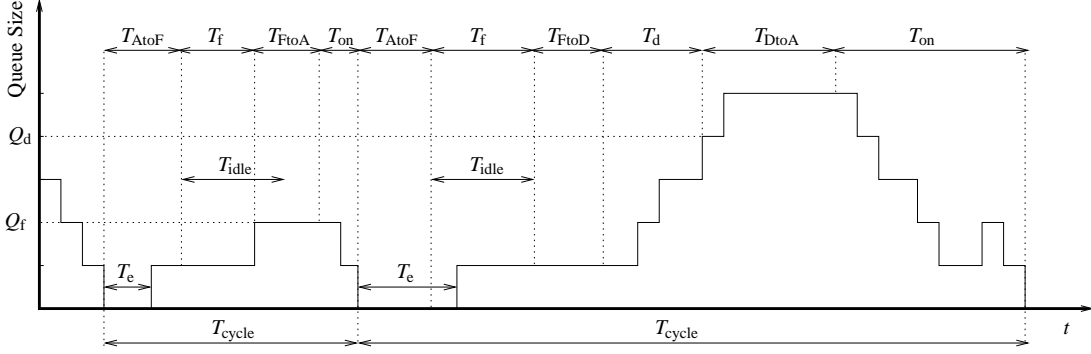


Fig. 2. Coalescing cycles with $Q_f = 2$ frames and $Q_d = 4$ frames.

where $A(\tau)$ is the number of frame arrivals in a time interval of duration τ .

C. Average Duration of Fast-Wake Periods

The duration of Fast-Wake periods depends on the arrival time of the Q_f -th frame. If this frame arrives before finishing the transition to Fast-Wake, then the interface will return to the active state without entering Fast-Wake at all. Conversely, the interface will stay in Fast-Wake until this frame arrives or the T_{idle} timer expires, whatever happens first. Therefore, the mean duration of Fast-Wake periods is given by

$$E[T_f] = \int_{T_{AtoF}}^{T_{AtoF}+T_{idle}} (t - T_{AtoF}) f_{Q_f}(t) dt + \int_{T_{AtoF}+T_{idle}}^{\infty} T_{idle} f_{Q_f}(t) dt, \quad (9)$$

where $f_{Q_f}(t)$ is the probability density function (pdf) of the time elapsed since the beginning of the coalescing cycle until the arrival of the Q_f -th frame. Since we are assuming independent and identically distributed interarrival times, $\{I_n\}$ is a renewal process and $f_{Q_f}(t) = f_{T_e}(t) * f_{I_2}(t) * \dots * f_{I_{Q_f}}(t) = f_{T_e}(t) * f_{I_1}(t)^{(Q_f-1)}$, where $*$ is the convolution operator, $f_{T_e}(t)$ is the pdf of the empty periods and $f_{I_1}(t)$ is the pdf of the time between the arrivals of two consecutive frames.

D. Average Duration of Deep-Sleep Periods

An interface in the Fast-Wake mode will only transition to Deep-Sleep when it receives less than Q_f frames during the $T_{AtoF} + T_{idle}$ period. Then, assuming that just i frames, $i < Q_f$, are received during the Fast-Wake period, the interface will remain in the Deep-Sleep mode until $Q_d - i$ more frames arrive. Therefore, with independent interarrival times, the mean duration of Deep-Sleep periods can be calculated as

$$E[T_d] = \sum_{i=0}^{Q_f-1} \Pr[A(T_{AtoF} + T_{idle}) = i] \int_{T_{FtoD}}^{\infty} (t - T_{FtoD}) f_{Q_d-i}(t) dt, \quad (10)$$

where $f_{Q_d-i}(t) = f_{I_{i+1}}(t) * f_{I_{i+2}}(t) * \dots * f_{I_{Q_d}}(t) = f_{I_1}(t)^{(Q_d-i)}$ is the pdf of the time elapsed since the arrival of the i -th frame until the Q_d -th frame arrives.

IV. POISSON TRAFFIC

In this section we will calculate the average lengths of the Fast-Wake, Deep-Sleep and transitioning periods when frame

arrivals follow a Poisson process. Although it is well-known that frame arrivals on LAN networks do not really follow a Poisson distribution [7], Poisson traffic is useful in order to provide a valid approximation to aggregated traffic in the Internet core [8].

According to Sect. III-B, to obtain the average length of the transitioning periods, it only remains to calculate the probability that the interface enters the Deep-Sleep mode (p_d). It is well known that, with Poisson traffic, $\Pr[A(\tau) = i] = e^{-\lambda\tau}(\lambda\tau)^i/i!$, so, substituting this into (8), we get

$$p_d = R(Q_f, \lambda(T_{AtoF} + T_{idle})) = \frac{\Gamma(Q_f, \lambda(T_{AtoF} + T_{idle}))}{\Gamma(Q_f)}, \quad (11)$$

where $R(q, x)$ is the regularized upper incomplete gamma function, $\Gamma(q, x) = \int_x^{\infty} t^{q-1} e^{-t} dt$ is the upper incomplete gamma function and $\Gamma(q) = \Gamma(q, 0)$.

Regarding the average duration of Fast-Wake periods, note that, due to the memoryless property of Poisson traffic, $f_{T_e}(t) = f_{I_1}(t)$, so $f_{Q_f}(t) = f_{I_1}(t)^{Q_f}$. Additionally, since for Poisson traffic all interarrival times are exponentially and identically distributed, the arrival time of the Q_f -th frame is Erlang- Q_f distributed and $f_{Q_f}(t) = \lambda^{Q_f} t^{Q_f-1} e^{-\lambda t} / (Q_f - 1)!$. Using this to solve (9), we get

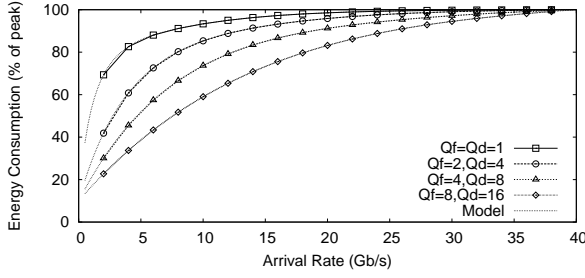
$$E[T_f] = Q_f (R(Q_f + 1, \lambda T_{AtoF}) - R(Q_f + 1, \lambda(T_{AtoF} + T_{idle})) / \lambda - T_{AtoF} R(Q_f, \lambda T_{AtoF}) + (T_{AtoF} + T_{idle}) p_d). \quad (12)$$

Finally, applying $f_{Q_d-i}(t) = \lambda^{Q_d-i} t^{Q_d-i-1} e^{-\lambda t} / (Q_d - i - 1)!$ into (10), we obtain that the average duration of Deep-Sleep periods is given by

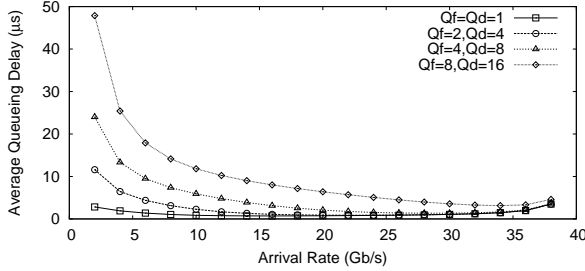
$$E[T_d] = \sum_{i=0}^{Q_f-1} \frac{e^{-\lambda(T_{AtoF}+T_{idle})} (\lambda(T_{AtoF}+T_{idle}))^i}{i!} \cdot ((Q_d - i) R(Q_d - i + 1, \lambda T_{FtoD}) / \lambda - T_{FtoD} R(Q_d - i, \lambda T_{FtoD})). \quad (13)$$

V. EVALUATION

To evaluate the performance of the proposed scheme and validate our model, we conducted several experiments on an in-house simulator, available for download at [9]. We simulated a 40 Gb/s interface receiving Poisson traffic with an average arrival rate varying from 2 to 38 Gb/s. The frame size was set to 1500 bytes. Regarding the PHY features, we set the transition times and the efficiency profile to the same values



(a) Energy consumption.



(b) Average queueing delay.

Fig. 3. Results with Poisson traffic.

as in [6]: $T_{\text{AtOF}} = 0.90 \mu\text{s}$, $T_{\text{FtoA}} = 0.34 \mu\text{s}$, $T_{\text{FtoD}} = 1.00 \mu\text{s}$, $T_{\text{DtoA}} = 5.50 \mu\text{s}$, $T_{\text{idle}} = 3.50 \mu\text{s}$, $\phi_f = 0.7$ and $\phi_d = 0.1$.

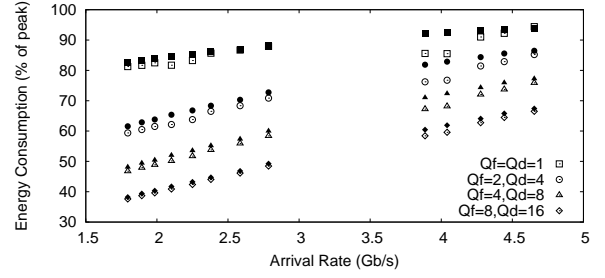
Figure 3 shows both the energy consumption and the average queueing delay obtained without coalescing ($Q_f = Q_d = 1$) and when coalescing is applied with three different queue threshold configurations.² Note that our model provides very accurate predictions for the energy consumption in all the simulated scenarios. As expected, frame coalescing significantly reduces energy consumption at the expense of increasing frame latency and the higher the queue thresholds are, the greater energy savings and frame delays are obtained.

We also evaluated frame coalescing using real world traffic traces publicly available from the CAIDA archive [10]. The analyzed CAIDA traces were collected during 2015 on a 10Gb/s backbone Ethernet link. Though 10 Gigabit links only have a single LPI mode, we assumed that the traced PHY behaves as the previously simulated dual-mode interface and uses the same configuration settings. Figure 4 shows the obtained results. Again, frame coalescing allows important reductions on energy consumption at the cost of tolerable increments on frame delay. Fig. 4(a) also shows the energy consumption predicted by our Poisson model. Not surprisingly, the model predictions are quite similar to the measured values, thus confirming the Poissonian-like nature of aggregated traffic.

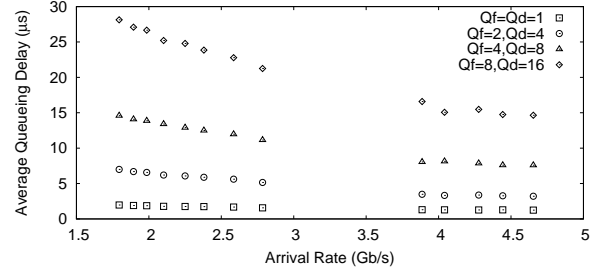
VI. CONCLUSIONS

This paper provides an accurate model for dual-mode EEE interfaces that can be used to analyze the influence of frame coalescing parameters and PHY characteristics on their energy

²Each simulation was run for ten seconds and repeated ten times using different random seeds. The average and 95% confidence intervals (CIs) of every performance measure were calculated but CIs have not been represented in the graphs since all of them are small enough and just clutter the figures.



(a) Energy consumption. Filled points show model predictions.



(b) Average queueing delay.

Fig. 4. Results for CAIDA traces.

consumption. Simulation results for both synthetic and real Internet traffic traces assess the validity of our model and confirm that frame coalescing allows significant energy savings at the cost of some tolerable increments on frame delay.

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